Using a volume Bragg grating instead of a Faraday isolator in lasers incorporating stimulated Brillouin scattering wavefront reversal or beam cleanup

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Abstract: A master-oscillator power-amplifier with stimulated Brillouin scattering (SBS) beam cleanup or wavefront reversal typically incorporates a Faraday isolator to outcouple the Stokes light, limiting the power scalability. Volume Bragg gratings (VBGs) have the potential for scaling to higher powers. We report here the results of tests on a VBG designed to resolve wavelengths 0.060 nm apart, corresponding to the 16 GHz frequency shift for SBS backscattering at 1064 nm in fused silica. Such an element may also find use in between stages of fiber amplifiers, for blocking the Stokes wave.

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14. ABSTRACT
A master-oscillator power-amplifier with stimulated Brillouin scattering (SBS) beam cleanup or wavefront reversal typically incorporates a Faraday isolator to outcouple the Stokes light, limiting the power scalability. Volume Bragg gratings (VBGs) have the potential for scaling to higher powers. We report here the results of tests on a VBG designed to resolve wavelengths 0.060 nm apart, corresponding to the 16 GHz frequency shift for SBS backscattering at 1064 nm in fused silica. Such an element may also find use in between stages of fiber amplifiers, for blocking the Stokes wave.

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1. Introduction

A master-oscillator power-amplifier (MOPA) with stimulated Brillouin scattering (SBS) wavefront reversal [1] requires an optical element to couple the seed into the amplifier and outcouple the Stokes wave after the second, backward pass through the amplifier. SBS beam cleanup has a similar requirement [2]. In both cases, a Faraday isolator is typically used because the laser and Stokes waves are counterpropagating. Alternatively, a volume Bragg grating (VBG) can separate the two based on the wavelength shift, just as in a conventional diffraction grating. Photo-Thermo-Refractive (PTR) glass can be made with a loss below 10^{-3} cm^{-1}, and a damage threshold above 10^4 W/cm^2, therefore VBGs have the potential for scaling to higher powers, provided the area is large enough [3,4].

A 6.3 mm-thick VBG has previously been used as the input coupler for a low quantum defect Yb:KYW laser [5]. An 18 mm-thick VBG was used to narrow the linewidth of a diode bar to 20 pm (10 GHz) at 780 nm [6]. A 3 mm-thick VBG was used as an input coupler for a low quantum defect Er:Sc_2O_3 laser [7]. We have designed and fabricated a 12 mm-thick VBG to resolve the 0.06 nm (16 GHz) Stokes shift in fused silica at 1064 nm. Initial testing has been carried out with up to 27 W incident upon the VBG.

In the *wavefront reversal* MOPA geometry, the Stokes beam is coupled out after the second pass amplification. A VBG could be used to reflect λ_L and transmit λ_S (Fig. 1). This geometry may have a more graceful failure mode in the event of a misalignment of the VBG, or an accidental shift in its resonance due to a change in temperature.

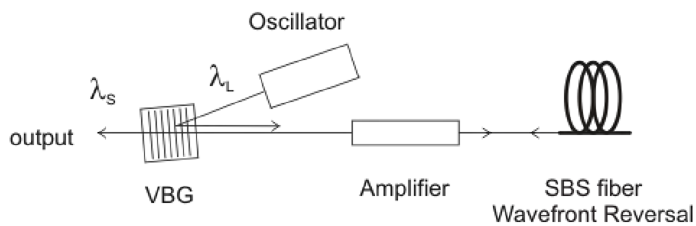

Fig. 1. The preferred configuration using a VBG to outcouple in the wavefront reversal geometry.

In the *beam cleanup* MOPA geometry, diffracting λ_L and transmitting λ_S would again have the more graceful failure mode, but for ease of alignment, transmitting λ_L is possible as well (Fig. 2).

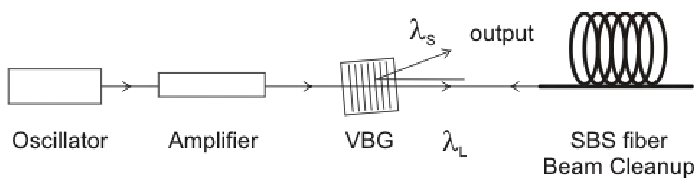

Fig. 2. A possible configuration to outcouple in the beam cleanup geometry.

2. Experiment & calculations

Our simulation with coupled wave theory shows that a 12 mm-thick grating should have sufficient resolution and an excellent contrast ratio. We then fabricated a sample and antireflection coated the 8 × 10 mm^2 entrance and exit faces. Low-power reflection measurements made with a tunable diode laser [8] agree well with the simulation (Fig. 3). The full width at half maximum (FWHM) of the simulation is 0.063 nm; the experimental data has a FWHM of 0.057 nm. The spectral selectivity of reflecting Bragg gratings widens if the efficiency is increased too much, so the VBG was designed to have a peak reflectivity below 0.95. Scattering losses are less than 1% and comparable to the residual reflectivity of the anti-reflection coated entrance and exit faces. The asymmetry in the side lobes of the measured

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curve could be due to a z-dependent background index change, or grating period distortion [9,10]. The polarization dependence of a volume holographic grating should be negligible when the angle between the incident and diffracted beams is <10° [11], and we have confirmed this experimentally.

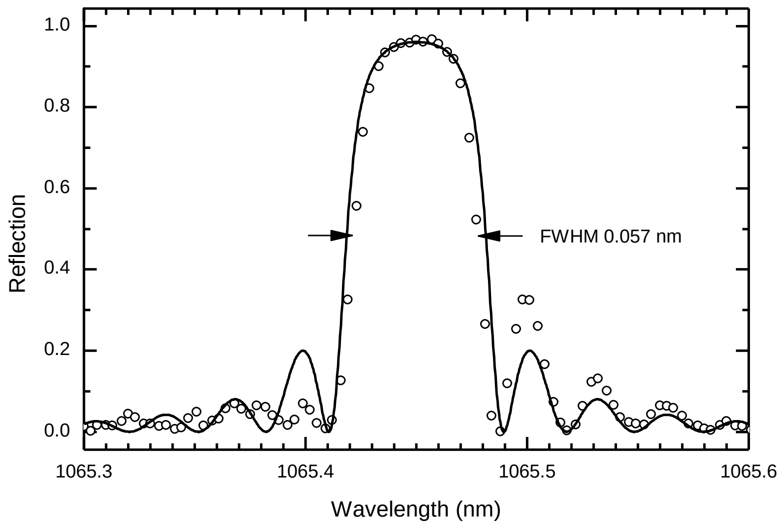

Fig. 3. Calculated (line) and measured (circles) reflection of a 12 mm-thick reflection volume Bragg grating.

For high-power testing, the VBG is mounted in a temperature-controlled holder with two rotation axes approximately normal to the grating vector. The source is a VBG-stabilized diode laser [12] amplified to 30 W with a single-mode, polarization-maintaining Yb-doped fiber amplifier [13]. The delivery fiber has a numerical aperture of 0.06; the output is collimated to a 3.0 mm diameter with a 25 mm focal length doublet [14]. A half-wave plate and Faraday isolator serve as a variable optical attenuator. To obtain the backward Stokes beam, light at λ_L is focused with a 30 mm focal length doublet into a 2.7 km graded-index fiber with a 50 μm core and numerical aperture of 0.2 [15]. Beam samplers at a small angle of incidence monitor incident, reflected, and transmitted powers. The VBG is aligned to maximize the Bragg reflection at an angle of 10°.

3. Results

High power measurements were taken in the geometry of Fig. 1 and of Fig. 2. Based on the low power measurements in Fig. 3, the figure of merit appropriate for Fig. 1, R_LT_S, could be as high as 0.96. The figure of merit appropriate for Fig. 2, T_LR_S, would be slightly less, 0.94, but easier to obtain experimentally because the short wavelength sidelobes in Fig. 3 are much smaller.

Measured in the geometry of Fig. 2, the VBG transmittance at λ_L is 0.95 and the VBG reflectance at λ_S is 0.94 at an input power of 27 W (Fig. 4). The figure of merit of the VBG is $T_LR_S = 0.89$. The light reflected from the fiber shows the characteristic threshold behavior of SBS. The highest SBS reflectance we observe is 0.81. The threshold is 0.2 W incident upon the fiber.

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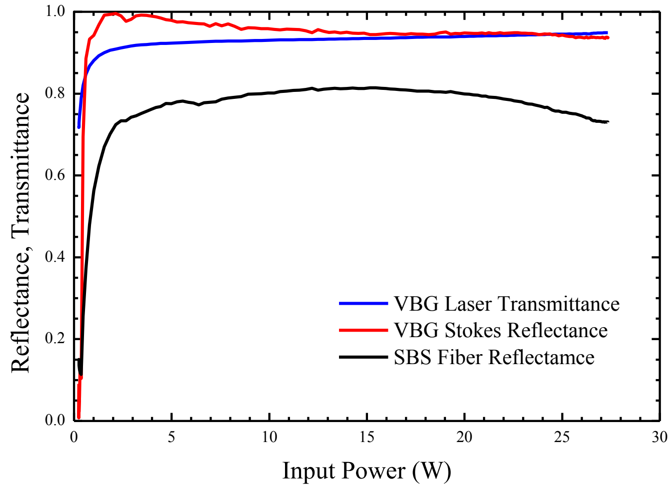

Fig. 4. The VBG transmittance at λ_L (blue), VBG reflectance at λ_S (red), and SBS reflectance (black).

We also tested the VBG in the geometry of Fig. 1 for input powers up to 7.5W. In this case, R_L is 0.95, and T_S is 0.88; both are nearly independent of input power. The figure of merit in this geometry is $R_L T_S = 0.84$.

4. Discussion

One issue is whether absorption will heat the VBG enough to shift the resonance. The index change and thermal expansion of photo-thermal refractive (PTR) glass are such that the resonant wavelength red shifts ~0.009 nm/°C at this spectral range. To investigate this we solved the 3D heat diffusion equation inside an 8×10×12 mm^3 piece of glass with specific heat 0.84 J/gm°C and thermal conductivity 1 W/m°C. An absorption coefficient $\alpha = 10^{-3}$ cm^{-1} corresponds to an absorption of 0.12%. Taking the case of a 100 W beam, we assume that 0.12 W is deposited uniformly in a cylinder 6 mm in diameter, centered in the sample, the two surfaces are in contact with a heat sink at 300 K, and there is no heat flow through the other four surfaces. The steady state results show a 1°C temperature difference between the beam axis and the 3 mm radius of the beam (Fig. 5, Fig. 6). This implies a 0.009 nm shift in resonance, which will produce only a small change in the transmission at λ_L and λ_S.

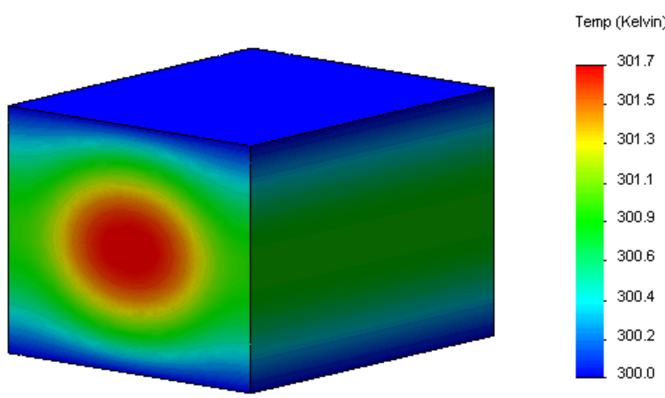

Fig. 5. Cross section of the steady state temperature profile inside an 8 × 10 × 12 mm^3 piece of PTR glass, with 0.12 W of heat deposited in a cylinder of the same length and 6 mm in diameter.

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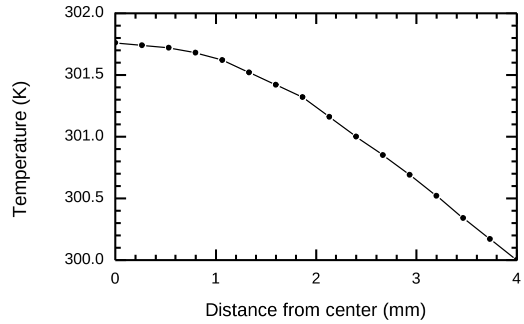

Fig. 6. Steady State VBG temperature vs distance along y from center of Fig. 5.

The thermal time constant, on the order of 15 s, limits the rate at which the output power of the laser can be changed (Fig. 7).

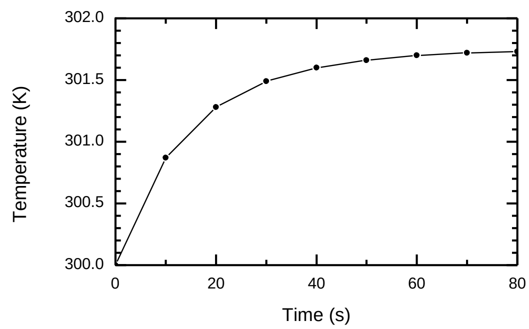

Fig. 7. Transient VBG temperature on axis, same conditions as Fig. 5.

4. Summary

The scalability of a high average power wavefront-reversing MOPA was previously limited by the 1-kW power handling capability of the commercial Faraday isolators used for outcoupling. Beam cleanup MOPAs have a similar limitation. Compared to a Faraday isolator, a volume Bragg grating made from photothermal refractive glass appears to be a more scalable option for outcoupling the Stokes beam. We tested a VBG designed to separate wavelengths 0.060 nm apart, corresponding to the Stokes shift in fused silica at 1064 nm. In the geometry of Fig. 1, we measured a laser reflectance of 0.95 and a Stokes transmittance of 0.88, at an incident power of 7 W. In the geometry of Fig. 2, we measured a laser transmittance of 0.95 and a Stokes reflectance of 0.94, at an incident power of 27 W.

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